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Hydrodynamic Breech Window Design Concept for Laser Ignition of Large-Caliber Guns

Stephen L. Howard
Lang-Mann Chang
John Grosh

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Stephen L. Howard,* Lang-Mann Chang,* and John Grosh**

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13. ABSTRACT *(Maximum 200 words)*

Laser ignition is becoming a viable method of igniting a propellant bed (especially for large-caliber guns). However, problems still are present at the optical interface of the laser and the round to be fired. The most obvious problem to the casual observer is the deposits left on the window from the ignition of the igniter material and propellant. If the window is obscured (by an opaque coating or by opaque particles), ignition of subsequent rounds may not be possible. Therefore, a method of keeping the window clean for an extended number of firings is needed. Instead of physically wiping the window after each firing, this study examined the use of hydrodynamic flow of the igniter gases to keep the obscuring particles and hot gases from making contact with the window. Initial experiments used visualization by water jets to validate theoretical predictions for deflecting the particle-laden fluid flow. Improvements to the basic design included a cyclonic chamber in the window region to remove particles. Predictions indicated that the maximum pressure in the cyclonic chamber would be about 75% of the maximum breech pressure. Designs were tested in both subscale (76-mm I.D.) and full-scale (155-mm I.D.) simulators made of optically clear polymer resins. Several of these designs dramatically reduced the amount of particles that reached the window area.

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1. INTRODUCTION

The laser ignition concept for initiating large-caliber ammunition was originally conceived and tested at the U.S. Ballistic Research Laboratory* at Aberdeen Proving Ground, MD 21005-5066 (Robitalle 1964; Barrows et al. 1993). The ability to ignite propellant beds by using laser radiation as the ignition source should eliminate the need for primers and simplify the ignition train of ammunition as well as improve the safety of the firing procedure.

However, if the laser radiation cannot reach the igniter material that subsequently ignites the propellant, the propellant cannot ignite. Important to all schemes that transmit laser radiation into the breech of a gun is an optical window. This window must be made of a material that transmits the laser radiation without deleterious effects to the material and must withstand the high-temperature, high-pressure, and chemically hostile environment of the breech during the ballistic cycle. In addition, the window material and/or design must eschew particles created during the ballistic cycle that would otherwise be deposited on the window. If particles remain on the window surface, the laser radiation transmission will be reduced for the subsequent firing (see Figure 1). At some point, if the window were not sufficiently cleaned, it would no longer transmit, and further firing would be impossible. Also, if thermal shock from contact with the hot gases were to occur, the window would crack and the pressure seal would be lost.

* On 30 September 1992, the U.S. Army Ballistic Research Laboratory (BRL) was deactivated and subsequently became part of the U.S. Army Research Laboratory (ARL) on 1 October 1992.

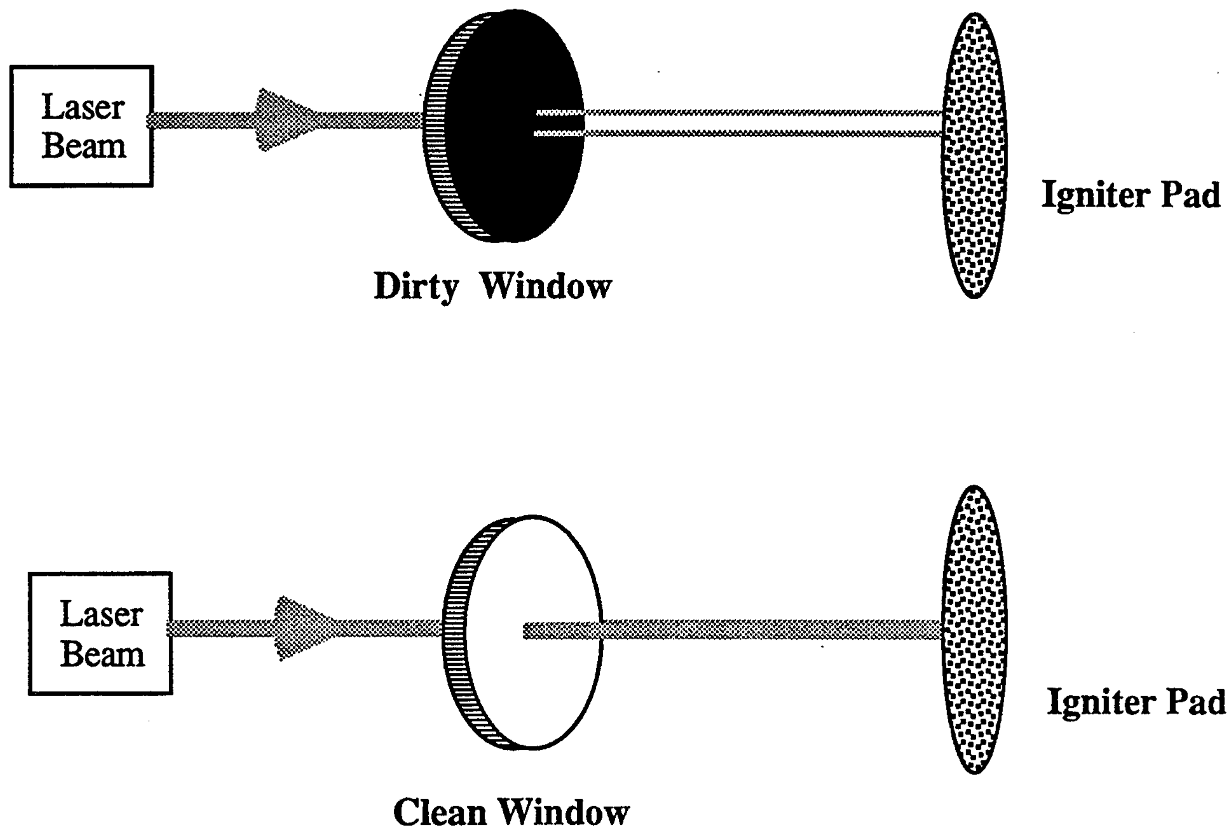


Figure 1. Effect of dirty window on laser ignition.

A cleaning procedure that required swabbing the window after each firing would not be acceptable for many reasons, the least of which is the requirement for rapid firing. Cleaning with a brush mounted on the breech should meet with only partial success. The brush would rapidly become contaminated and in a steady-state condition would leave particles on the window as it brushes others away. Therefore, a breech brush would require frequent replacement in order to avoid the steady-state condition.

A cleaning procedure that would work with only a subset of the ammunition (those that require a stub base) would be a double window. If a window were mounted in the stub base as well as in the breech, the stub base window should provide an optically clean screen for the breech window that would be thrown away with every round. Such a procedure would dramatically increase the cost of ammunition since acceptable windows are not inexpensive. This paper presents a change in paradigm from the aforementioned methods. A technique that uses the gases from propellant combustion to keep the window clean is discussed. Hydrodynamic forces will always be present in a gun as long as propellant and hot, high-pressure gases are used to propel the projectile. If a cavity is placed in the spindle, these forces can be utilized to keep the window clean.

2. CALCULATION OF PRESSURE IN THE CAVITY

Figure 2 schematically represents the flow system composed of the cavity in the spindle and the gun chamber. The two flow volumes are connected by two orifices of equal diameter. During the early phase of the interior ballistic cycle, the pressure in the gun chamber rises following the combustion of the propelling charge. A flow of propellant gases to the cavity through the orifice then occurs. At some point in the ballistic cycle after the gun chamber pressure has reached its peak value, the pressure in the cavity becomes higher than that in the gun chamber. The flow reverses its direction until the end of the interior ballistic cycle.

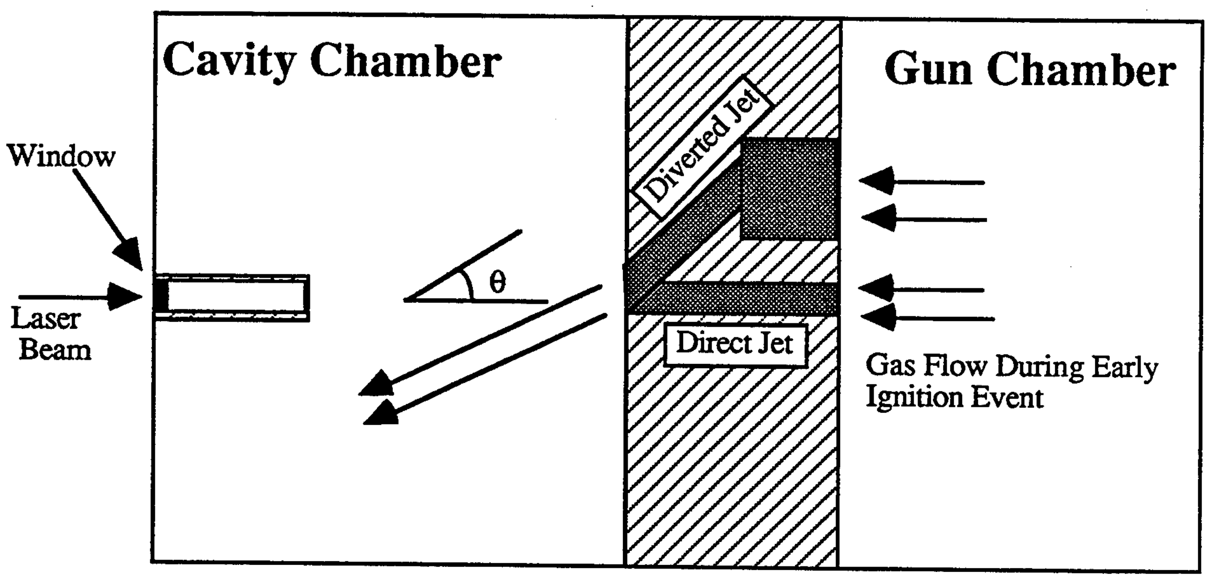


Figure 2. Proposed flow system for hydrodynamic cleaning of window.

Since the gas flow through the orifice is a flow with high Reynolds numbers, it is appropriate to consider the flow as a one-dimensional, inviscid flow system for the primary interest of predicting the pressure rise in the cavity. The following sections contain the governing equations for the flow system.

2.1 Equation of State. The Nobel-Abel equation of state is adopted and written as:

$$P_c = \frac{R_u \, T_c \, W}{V_c \; m \; - \; b \; W} \;, \tag{1}$$

where P_c, Tc, W, and V_c are the pressure, temperature, total mass, and volume of the cavity, respectively. Furthermore, m , b, and R_u are the molecular weight, covolume, and universal gas constant of the propellant gases, respectively.

2.2 Continuity Equations. It is noted that there are two modes, choked and nonchoked, of flow through the orifice during the interior ballistic cycle. A choked flow occurs when

$$\frac{P^*}{Po} = [\frac{2}{k+1}]^{k/(k-1)} \quad , \tag{2}$$

where P^* = pressure of expanding fluid at which a choked flow occurs, P_o , T_o equal the pressure and temperature in gun chamber, and k = ratio of specific heats. For propellant gases, k = 1.243, and the pressure ratio in equation (2) is calculated to be 0.556. In the equation, P_o can be obtained from calculations using XKTC code or others (Gough 1986).

2.2.1 Flow From the Gun Chamber to the Cavity. When $\frac{P_c}{P_o} \leq 0.556$ (choked flow): The flow rate through the orifice is (Shapiro 1953)

$$\dot{\omega} = C_d \, A \, \frac{P_o}{\sqrt{T_o}} \sqrt{\frac{kg}{R_u} \, [\frac{2}{k+1}]^{(k+1)/(k-1)}} \quad , \tag{3}$$

where C_d = discharge coefficient of orifice, A = cross-sectional area of orifice, and g = gravity.

When $\frac{P_c}{P_o} > 0.556$ (nonchoked flow): The flow rate is

$$\dot{\omega} = C_d \, A \sqrt{\frac{kg}{R_u}} \frac{P_c}{\sqrt{T_o}} M \sqrt{1 + \frac{k-1}{2} M^2} \;, \tag{4}$$

where M = Mach number given as

$$M = \sqrt{\frac{2}{k-1} [(\frac{P_o}{P_c})^{(k-1)/k} - 1]} \quad . \tag{5}$$

2.2.2 Flow from the Cavity to the Gun Chamber. When $\frac{P_o}{P_c} \leq 0.556$ (choked flow): The flow rate is

$$\dot{\omega} = -C_d A \frac{P_c}{\sqrt{T_c}} \sqrt{\frac{kg}{R_u} [\frac{2}{k+1}]^{(k+1)/(k-1)}} \quad . \tag{6}$$

When $\frac{P_o}{P_c} > 0.556$ (nonchoked flow): The flow rate is

$$\dot{\omega} = -C_d A \sqrt{\frac{kg}{R_u}} \frac{P_o}{\sqrt{T_c}} M \sqrt{1 + \frac{k-1}{2} M^2} \tag{7}$$

with

$$M = \sqrt{\frac{2}{k-1} [(\frac{P_c}{P_o})^{(k-1)/k} - 1]} \quad . \tag{8}$$

2.3 <u>Energy Equations</u>.

2.3.1 Flow From the Gun Chamber to the Cavity. For either a choked or nonchoked flow, the rate of temperature change in the cavity is

$$\dot{T}_c = \frac{\dot{\omega}}{WC_v} [(1-\phi)\, C_p\, T_o - C_v\, T_c] \quad , \tag{9}$$

where ϕ = heat loss to the walls of the cavity, including the orifice area; C_p = constant pressure specific heat; and C_v = constant volume specific heat.

2.3.2 Flow From the Cavity to the Gun Chamber.

$$\dot{T}_c = \frac{\dot{\omega} T_c}{WC_v} (C_p - C_v) \quad . \tag{10}$$

3. EXPERIMENTAL

3.1 Water Jet Simulator. Initial visualizing of the diverted jet concept was performed using water. Figure 3 shows a water tank with provisions for pressurized water addition as well as a removable bottom plate that contained the jet orifices. Plates were tried with angles of 30°, 45°, and 60° (see Figure 2) between the jets. The larger angles required a two-stage structure for the diverting jet orifice. Otherwise, at large angles the entrance to the diverting jet would be too far from the direct jet. Therefore, a large entrance was drilled part way through the plate and was parallel to the direct jet. The diverting jet was then drilled so as to intersect the entrance hole and the exit of the direct jet

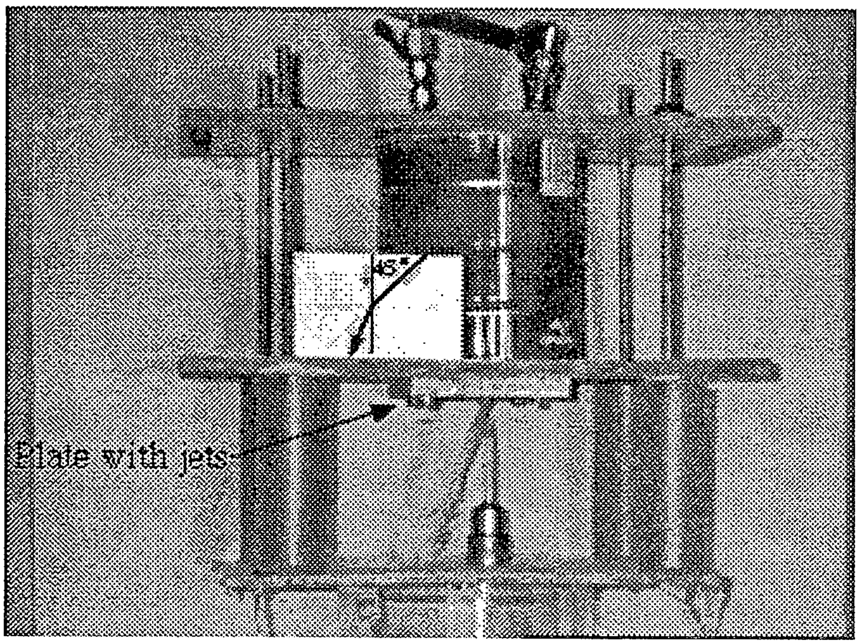


Figure 3. Schematic of water jet visualization system.

(see Figure 2).The tank system was supported by four acrylic tubes over a drainage system. Operation of the system was then videotaped.

3.2 Flamespread Chamber. For subscale tests, the flamespread chamber (Figure 4) was used (Kooker, Chang, and Howard 1992; Kooker, Howard, and Chang 1994). The flamespread chamber consisted of a transparent acrylic tube (interior diameter of 76 mm with an axial dimension of 305 mm) contained in a steel confinement casing. Ports were machined in the steel casing and the acrylic tube for pressure transducers.

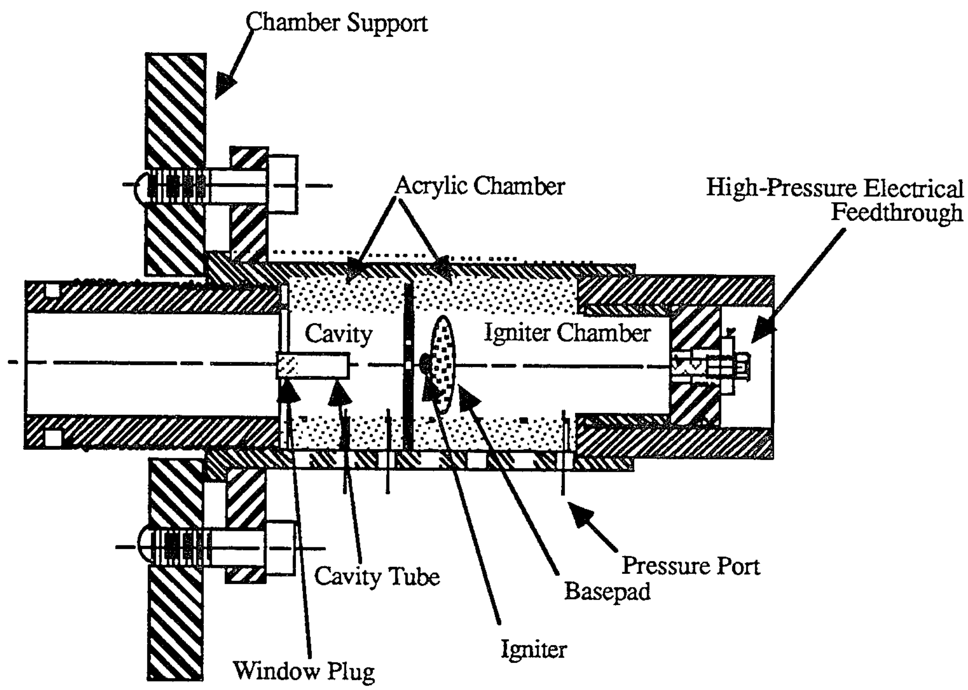


Figure 4. Cross-sectional view of flamespread simulator with cavity and igniter chambers.

For these experiments, the acrylic tube was split into two regions (igniter and breech window regions). The igniter region of the tube was closest to the right side of the simulator and contained a cloth basepad (containing black powder, ball powder, or clean burning [CBI] material). The basepad was ignited by a low-shock igniter located on the outside of the basepad facing the breech region so that laser ignition could be modeled (see Figure 4). A pressure transducer was located in each chamber. Other pressure transducers were located in various parts of the chamber, simulating the laser breech window area. The low-shock igniter was electrically connected to the firing line via a high-pressure electrical feedthrough in the top of the simulator. The chamber was also placed on the horizontal to approximate typical tank or artillery use.

The window region was experimentally modelled by a 4.25-mm O.D. aluminum plug (a threaded right-circular cylinder) that was highly polished on one end to form a witness plate and slotted on the other end so that it could be screwed out of the hollow tube for viewing (the hollow tube was made of aluminum and was internally threaded at the window region so that it could tightly hold the witness plate in place). The plug was chosen so that a leak-proof seal could be maintained in the window region and yet allow easy access to the witness plate for evidence of residues from the igniter material combustion.

3.3 Full-Scale Simulator. The full-scale simulator was a 165-mm interior diameter by 1,000-mm-long acrylic tube with aluminum end plates held in place by four threaded rods (see Figure 5). The igniter chamber was scaled up from the subscale simulator chamber. The conical cavity chamber was cast in the bottom of the acrylic tube with an aluminum cover plate that contained the jet orifices and isolated the cavity from the main chamber that contained the basepad. The casting material was a pourable polystyrene-polyester mix that was transparent upon solidification. Operation of the full-scale simulator was identical to that of the subscale simulator.

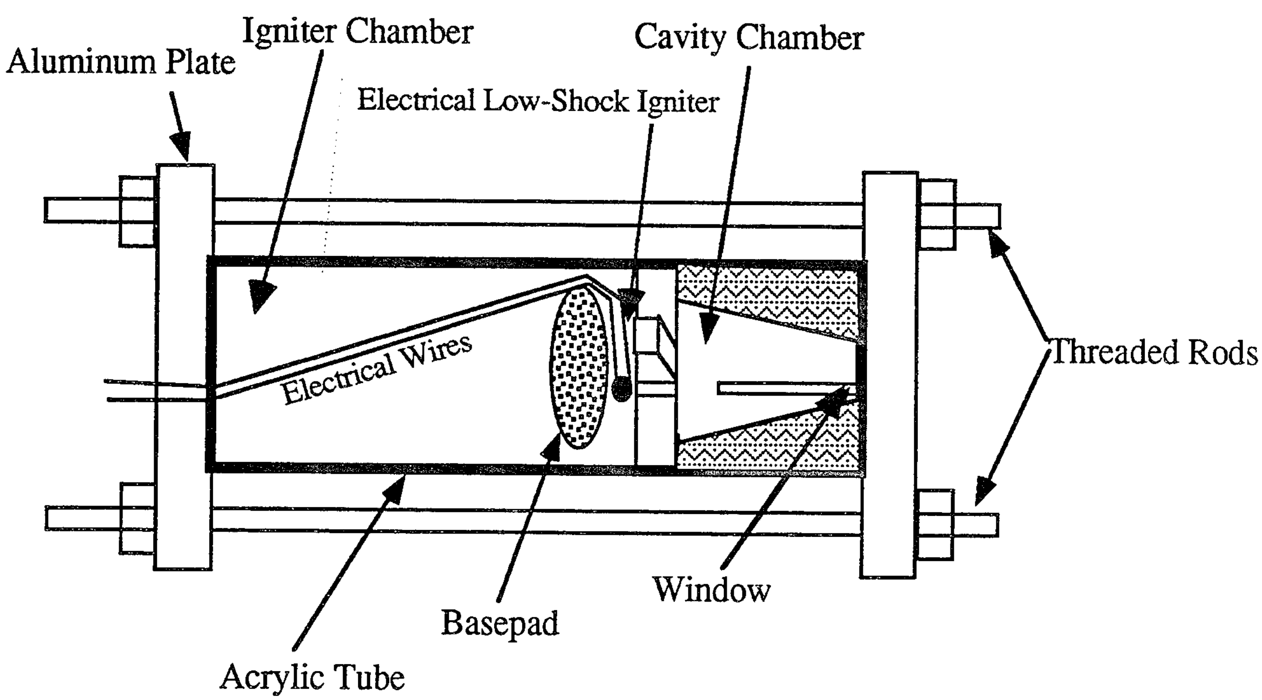


Figure 5. Schematic of full-scale simulator.

4. RESULTS AND DISCUSSION

4.1 Calculations. The governing equations described previously can be integrated numerically using a conventional integration method (see Appendix). The input data for the computer program are:

Discharge coefficient of orifice $C_d = 0.62$
Cross-sectional area of the orifice $A = 0.0000565$ m^2
Ratio of specific heats, $k = 1.243$
Volume of cavity, $V_c = 0.0000872$ m^3 and 0.000127 m^3
Specific covolume, $b = 0.00103$ m^3/kg
Molecular weight, $m = 23.4$ kg/kg-mole
Constant volume specific heat, $C_v = 456$ J/K-kg
Constant pressure specific heat, $C_p = 566$ J/K-kg
Gravitational acceleration, $g = 9.81$ m/s^2
Conversion factor, $J = 778$
Universal gas constant, $R_u = 8314$ J/K kg-mole
Initial pressure in the cavity, $P_{co} = 0.101$ MPa
Initial temperature in the cavity, $T_{co} = 295$ K
Heat loss to the cavity walls, $\phi = 0.1$ and 0.2 .

Note that the cross-sectional area, A, given here is the combined cross-sectional area of the two orifices in the window design, each with a diameter of 4.25 mm (0.165 inch). This diameter is sufficient for a laser beam to pass through. It is possible to open a cavity inside the spindle with a volume, V_c, ranging from 0.0000872 to 0.000127 m^3 without causing a structural failure of the spindle upon high-pressure loadings during the ballistic cycle. As for heat loss to the cavity walls, ϕ is difficult to accurately determine without conducting a complex three-dimensional flow analysis. However, from experience gained from closed bomb testing of propellants, it is reasonable to assume the heat loss to be in the range of 10 to 20% of the total energy entering the two orifices. In a continuous firing series, the heat loss will decrease accordingly.

A smaller V_c will result in a higher pressure rise in the cavity. Figure 6 presents calculated pressure rises in the cavity with $Vc = 0.000127$ m^3 corresponding to two assumptions of heat loss. During the interior ballistic cycle, the maximum pressure differentials between the gun chamber and the cavity, $\Delta P = P_o - P_c$, are 180 MPa and 200 MPa for $\phi = 0.10$ and $\phi = 0.20$, respectively. Based on the larger value of these two pressure differentials, the shear stress, S, across the solid between the gun chamber and the cavity is calculated by Equation 11.

$$S = \frac{\Delta P \ A_1}{A_2} \quad , \tag{11}$$

where A_1 is the surface area on which the pressure, ΔP, applies and A_2 is the cross-sectional area across the solid. The values of A_1 and A_2 for the proposed cavity are

0.00310 m^2 and 0.00501 m^2, respectively. The resulting maximum shear stress on the interface between the gun chamber and the cavity chamber is 124 MPa.

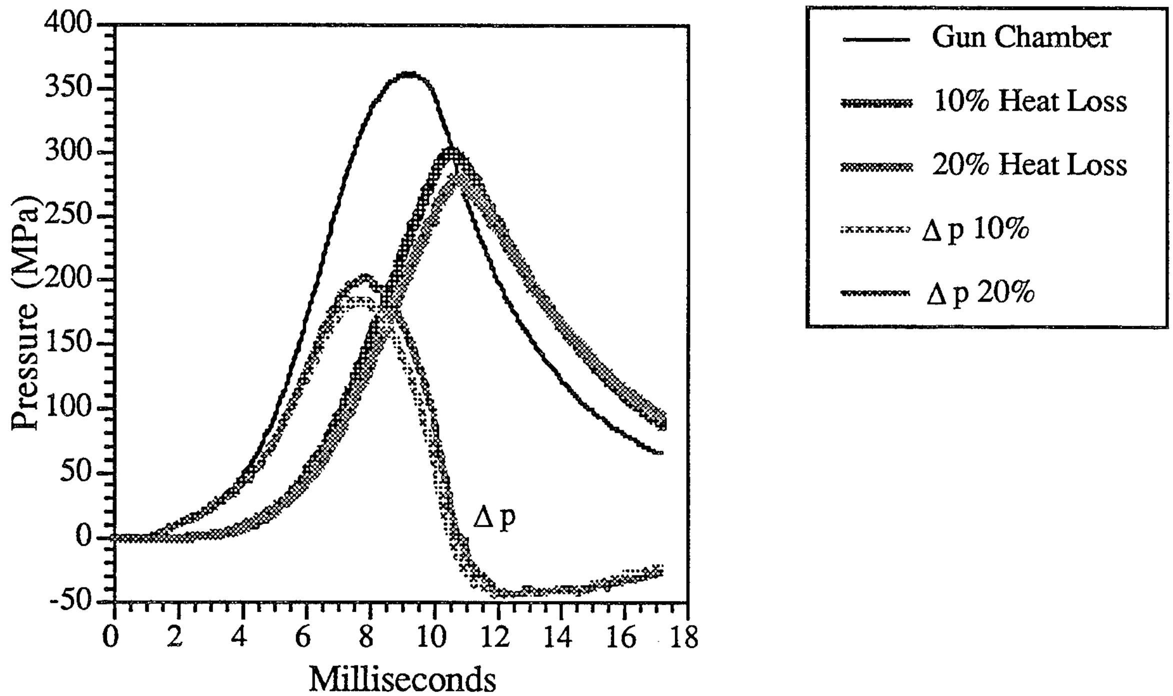
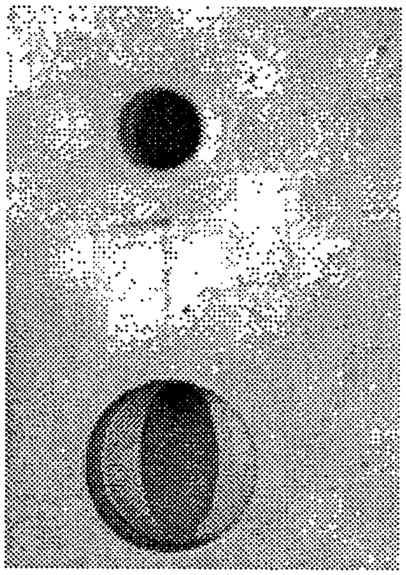


Figure 6. Pressure and Δp curves of gun chamber and cavity chamber with heat losses of 10% and 20%.

4.2 Water Jets. The water tank was connected to the domestic water supply at a pressure of approximately 0.3 MPa (40 psig). The tank was vented and the water flow from the exit orifices observed. The flow was diverted at an angle from the direct jet orifice (see also Figures 2 and 3). The diverting angle was slightly less than half the angle of the diverting jet. This result was expected. At a diverting jet angle of 60°, the diverted distance was greatest for the angles tested. The water jet appeared to completely miss the region where the window would be placed (see the object under the jets in Figure 3). The angle of 60° was the largest angle possible for the machining techniques utilized. Therefore, this angle was chosen for further study in the simulators.

4.3 Flamespread Chamber (Subscale Simulator). The first tests with the subscale simulator used a simple chamber (a right-circular cylinder) for the cavity (see Figure 4). A baseline test with Class 3 black powder was run with only a direct jet (e. g., the diverting jet was not completely drilled) and without the cavity tube shown in Figure 4.

The black powder residue particles were captured on a mylar sheet placed over the window orifice. Comparison of the before and after photographs in Figure 7 of the orifice entrances showed that black powder residue in the gun chamber portion of the simulator is indeed very dirty. As shown in Figure 8, the number of particles that passed through the direct jet was quite large. It is doubtful that a laser beam penetrating this residue layer (without first a cleaning procedure) could successfully ignite an igniter pad.



(a)

(b)

Figure 7. Before (a) and after (b) photographs of orifice entrances.

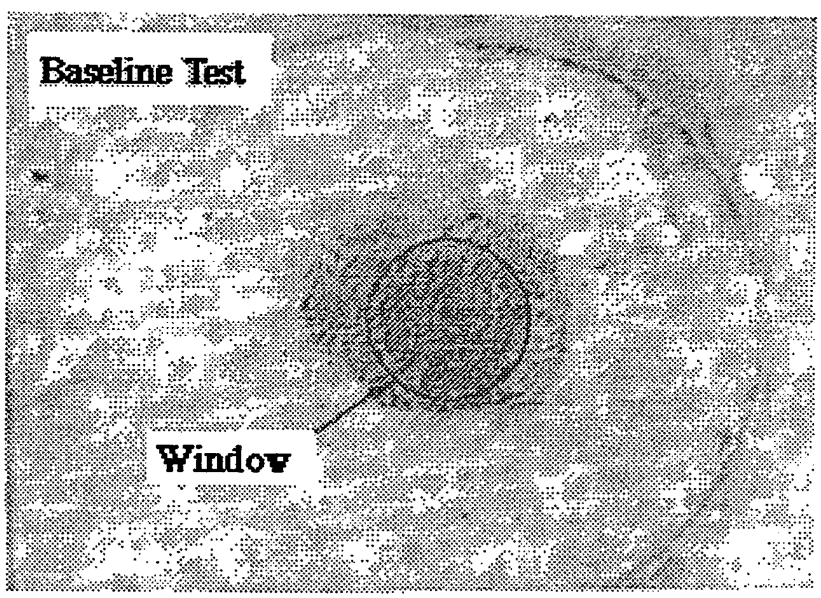
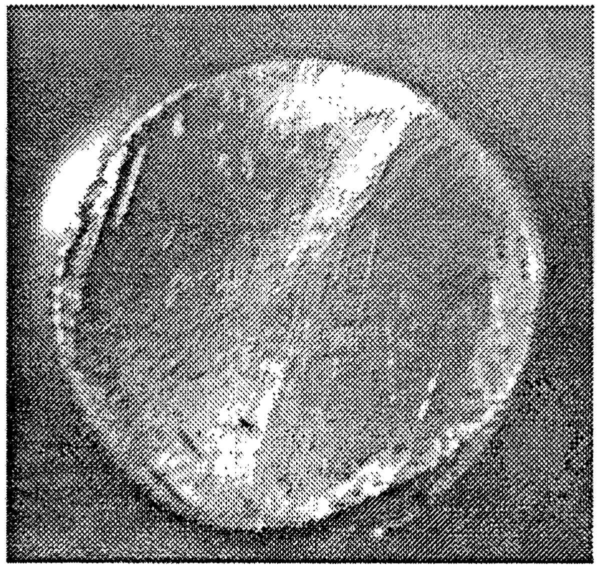


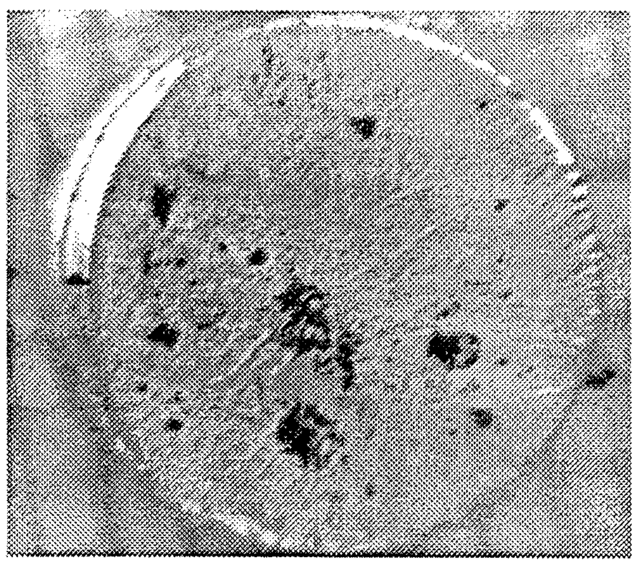
Figure 8. Black powder residue particles collected at window in baseline test.

In addition to not directly hitting the window region by the opening of the diverting jet for the remainder of the tests, the igniter gases were prevented from directly contacting the window witness plate by placing a hollow tube of 4.25-mm I.D. tube that extended from the window witness plate to nearly the exit of the orifices that form the jets (see Figures 2 and 4). It was thought that the initial air in the tube would act as a "buffer" that would compress as igniter gases entered the cavity chamber, thereby preventing a direct path to the window for both particles and hot gases. These tests also used Class 3 black powder in the basepad.

This particular technique drastically reduced the particles that attached to the window region. However, protection of the window was not particularly successful. A slight film and a large number of particles still covered the window witness plate (see Figure 9b). Fortunately, it was noted that the majority of particles in the diverted gas flow hit the chamber wall and then appeared to flow back toward the front of the cavity. It was posited that this recirculating flow carried the particles that finally attached to the window. Borrowing technology commercially available for separating particles from gas flows, the cavity chamber was changed from a right-circular cylinder to a tapered cone with the minimum diameter in the window region. This shape formed a hydrocyclone (see Figure 10a) that would separate particles from a tangential gas flow. While the diverted flow into the cavity chamber is not purely tangential, the flow becomes largely tangential upon impacting the curved wall of the cone. The tangential velocity component increases if the diverting jets are offset from the center of the cone. Fortunately, such is the case for the breech spindle currently in use for 155-mm cannon–the primer hole is offset by 14 mm to accommodate such features as the Swedish notch.

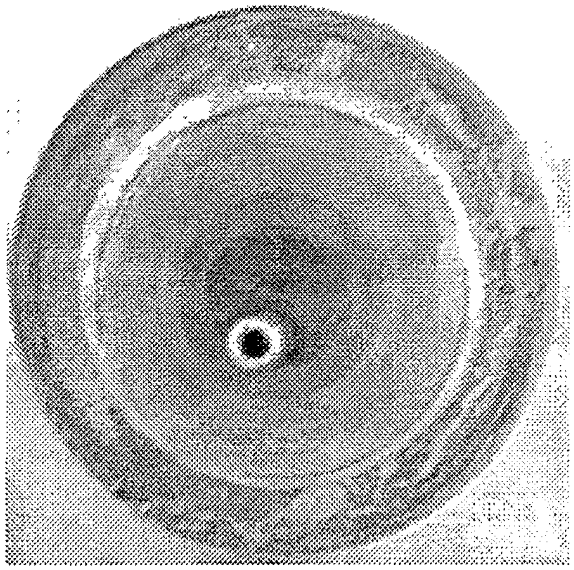


(a)

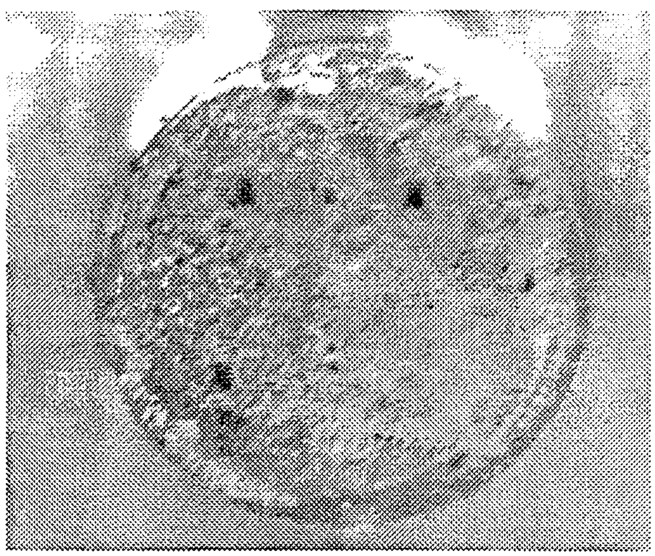


(b)

Figure 9. Before (a) and after (b) photographs of window witness plate.



(a)



(b)

Figure 10. Hydrocyclone chamber (a) and window witness plate (b).

This technique reduced to single digits the number of particles that finally found the window (see Figure 10b). When clean-burning igniter (CBI) material instead of black powder was used, particles were not noticed on the window witness plate. It was decided that black powder represented the worst case. An experiment was then tried with ten consecutive shots of black powder before examining the witness plate. The witness plate had few particles and was only slightly filmed. A larger number of shots would have been needed before laser light would begin to be seriously attenuated. Fortunately, at low rates of loading of the window the laser can burn off some of the contaminates as it ignites successive shots, thereby increasing the total number of shots before cleaning of the window.

4.4 Full-Scale Simulator. The full-scale simulator was made to resemble the end of the breech chamber and the spindle face in a 155-mm cannon. The simulator utilizing the conical cavity chamber showed no deviation from the results of the subscale simulator. As evidenced by residue particles that attached themselves to the wall of the conical chamber, the gas flow from the diverting jet avoided the window region and appeared to move in a circular path in the cavity chamber. The window region remained essentially clean (similar to the witness plate in Figure 10b) while using black powder as the igniter material.

5. SUMMARY

Both liquid- and gas-phase jets exiting from a pressurized chamber into a second gas-filled chamber of lower pressure can be diverted from the line-of-sight through the jet orifices. This concept was used in a 155-mm cannon simulator to reduce the dirt and thermal shock that can affect the window used for laser ignition. Gases emanating from an igniting basepad that would otherwise impinge upon and obscure the window were diverted. The gases were further processed by centrifugal force within a conical cavity next to the window to remove solid particles from the gas flow that could otherwise attach to the window. An air buffer zone just above the window was also provided. These two techniques kept hot, dirty gases from the window. They should be effective in protecting the window from thermal shock and from becoming dirty, which would block the laser beam required to ignite the basepad.

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APPENDIX:

FORTRAN PROGRAM CODE

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There are three files:

```
source.f      = source code listing
data.inc      = include file
constants.inc = include file
```

"Include" files are pieces of code which get inserted into the program at compilation. Constants and common block information were placed into these files.

To compile the code, SLATEC libraries must be installed on the system.

```
f77 -o chamber source.f /usr/lib/slatec/lib/slatec.a
```

The SLATEC (acronym for Sandia, Los Alamos, Air Force Weapons Laboratory Technical Exchange Committee) mathematic libraries perform a wide variety of functions such as solving linear systems of equations, ordinary and partial differential equations, spline interpolation, etc. This FORTRAN library is in the public domain and can be obtained from the following organization:

Energy Science and Technology Software Center
P.O. Box 1020
Oak Ridge, TN 37831
Telephone 615-576-2606
E-mail: estsc%a1.adonis.mrouter@zeus.osti.gov

The following codes were compiled on an Silicon Graphics Indigo. Silicon Graphics Inc. freely distributes the SLATEC libraries for their workstations and file servers.

```
==============================================================
          Filename: source.f
==============================================================
      PROGRAM CHAMBER

C-----------------------------------------------------------
C State Variables:
C
C PC   = chamber pressure (psi)
C TC   = chamber temperature (R)
C W    = mass in chamber (lb)
C Tdot = time derivative of temperature (R/s) in chamber
C Wdot = time derivative of mass (lb/s) in chamber
```

```
C------------------------------------------------------------
C Time-dependant parameters:
C
C P0 = gun chamber pressure (psi)  - from XKTC lookup table
C T0 = gun chamber temperature (R) - from XKTC lookup table
C------------------------------------------------------------
C Initial Conditions:
C
C PC0   = initial chamber pressure (lbf/ft^2)
C TC0   = initial chamber temperature (R)
C W0    = initial mass in chamber (R)
C time0 = start time (ms)
C timef = end time (ms)
C------------------------------------------------------------

      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      DOUBLE PRECISION K,M

      EXTERNAL DDASSL
      EXTERNAL RES,EOSW,DYNAM

      INTEGER NEQ,NG,MAXORD,LIW,LRW

      PARAMETER(N      = 15)
      PARAMETER(NEQ    = 3)
      PARAMETER(MAXORD = 5)
      PARAMETER(LIW    = 20+NEQ)
      PARAMETER(LRW    = 40+(MAXORD+4)*NEQ+NEQ**2)

      INTEGER INFO(N), IDID, IWORK(LIW), IPAR

      DOUBLE PRECISION TIME, TIME0,TIMEF, TIMEOUT,
     &           Y(NEQ), YPRIME(NEQ),
     &           RTOL, ATOL,RWORK(LRW), RPAR

      LOGICAL IFLAG
```

```
      SAVE JLO

c     Common blocks for input data.

#include "data.inc"

      CALL GETDATA()

      PC0 = PRESX(1)
      TC0 = TEMPX(1)
      CALL EOSW(PC0,TC0,W0)

      TIME0 = TIMEX(1)
      TIMEF = TIMEX(NDATA)
      NPTS  = 1000
      DTIME = (TIMEF-TIME0)/(NPTS)

      RTOL = 1.0D-06
      ATOL = 0.0D0

      CALL DYNAM(YPRIME(1),YPRIME(2),TIME0,PC0,TC0,W0)

      YPRIME(3) = 0.0D0

c     set initial conditions

      Y(1) = W0
      Y(2) = TC0
      Y(3) = PC0

      CALL SETINFO(INFO)

      TIME    = TIME0
      TIMEOUT = TIME + DTIME

      CALL OUT(TIME,TIMEOUT,Y,YPRIME,TC0,PC0)
```

```
      DO 100 I = 1, NPTS-1
        CALL DDASSL (RES, NEQ, TIME, Y, YPRIME, TIMEOUT,INFO,
     &               RTOL, ATOL, IDID, RWORK, LRW, IWORK,
     &               LIW, RPAR, IPAR, JAC)
        CALL INTERP(TIMEX,TEMPX,PRESX,NDATA,TIME,T0,P0)
        CALL OUT(TIME,TIMEOUT,Y,YPRIME,T0,P0)

        TIME    = TIMEOUT
        TIMEOUT = TIME + DTIME
100   CONTINUE

      END

c     -------------------------------------------------------------
      SUBROUTINE SETINFO(INFO)

c     Purpose:  initialize information array

      INTEGER INFO(15)
      DO 100 I = 1, 15
        INFO(I) = 0
100   CONTINUE

      END

c     -------------------------------------------------------------
      SUBROUTINE OUT(T,TOUT,Y,YPRIME,T0,P0)

c     Purpose: print out results

      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      DOUBLE PRECISION Y(*),YPRIME(*),PHAT

      PHAT = P0/Y(3)
       WRITE(6,'(11E20.10)') T,Y(3)/144.0D0,Y(2),Y(1),T0,P0/144.0,
```

```
     &          PHAT,YPRIME(1),YPRIME(2),YPRIME(3),1.0D0/PHAT

      END


      SUBROUTINE GETDATA()

c     Purpose: read in input data

      CHARACTER*80 FILENAME

#include "data.inc"

      READ(*,*) FILENAME
      READ(*,*) FLOSS
      READ(*,*) Vc
      READ(*,*) A
      READ(*,*) Cd

       OPEN(20,FILE='xktc.data')
      REWIND(20)
      DO 100 I = 1, NMAX
        READ(20,*,END=200) TIMEX(I), PRESX(I), TEMPX(I)

c       convert pressure from psi to lb/ft^2
        PRESX(I) = 144.0 * PRESX(I)
100   CONTINUE

200   NDATA = I - 1

      END
      SUBROUTINE RES(T,Y,YPRIME,DELTA,IRES,RPAR,IPAR)

      DOUBLE PRECISION Y(*),YPRIME(*),DELTA(*)
      DOUBLE PRECISION P0,T0,TC,PC,W,WDOT,PDOT,TDOT
```

```
      EXTERNAL EOSP, DYNAM

      W  = Y(1)
      TC = Y(2)
      PC = Y(3)

c     compute dynamic variables

      CALL DYNAM(WDOT,TDOT,T,PC,TC,W)

c     compute pressure from equation of state

      CALL EOSP(PC,TC,W)

      DELTA(1) = YPRIME(1) - WDOT
      DELTA(2) = YPRIME(2) - TDOT
      DELTA(3) = Y(3) - PC

      END


      SUBROUTINE DYNAM(WDOT,TDOT,TIME,PC,TC,W)

c     Describe dynamic equations for system

      DOUBLE PRECISION P0,T0,TC,PC,W
      DOUBLE PRECISION WDOT,PDOT,TDOT,PHAT,TIME,M

c     common black for input data

#include "data.inc"
#include "constants.inc"

C     Obtain gun chamber pressure and temperature from lookup table:

      CALL INTERP(TIMEX,PRESX,TEMPX,NDATA,TIME,P0,T0)
```

```
C    Compute time derivative of mass in chamber.  Note that
C    PHAT < 0.556 implies choked flow. For P_gun > PC,

     IF (P0 .GE. PC) THEN
       PHAT = PC/P0
       IF (PHAT .GT. 0.556D0) THEN
         M = dsqrt(((-1.0D0 + (1.0D0/PHAT)**((k-1.0D0)/k))
    &          *2.0D0/(k-1.0D0)))

         Wdot = Cd * A * dsqrt(k * g / R) * (PC / dsqrt(T0)) *
    &          M * dsqrt(1.0D0 + 0.5D0 * (k-1.0D0) * M**2)
       ELSE
         Wdot = Cd * A * dsqrt( (k * g / R) *
    &          ((2.0D0/(k+1.0D0))**((k+1.0D0)/(k-1.0D0))))
    &          *P0/dsqrt(T0)
       ENDIF
       Tdot = (Wdot/(W*Cv)) * (Cp*T0*floss - Cv*TC)
     ELSE
       PHAT = P0/PC
       IF (PHAT .GT. 0.556D0) THEN
         M = dsqrt(((-1.0D0 + (1.0D0/PHAT)**((k-1.0D0)/k))
    &          *2.0D0/(k-1.0D0)))

         Wdot = -Cd * A * dsqrt(k * g / R) *
    &          (P0 / dsqrt(TC)) * M * dsqrt(1.0D0+0.5D0*
    &          (k-1.0D0)*M**2)
       ELSE
         Wdot = -Cd * A * dsqrt( (k * g / R)*
    &        ((2.0D0/(k+1.0D0))**((k+1.0D0)/(k-1.0D0))))
    &        *PC/dsqrt(TC)

       ENDIF
       Tdot = (Wdot/(W*Cv)) * TC * (Cp - Cv)
     ENDIF
```

```
      END


      SUBROUTINE EOSP(PC,TC,W)

c     equation of state for computing chamber pressure

      DOUBLE PRECISION PC,TC,W

#include "data.inc"
#include "constants.inc"

      PC = Ru * TC * W / (Vc * MW - b * W)

      END


      SUBROUTINE EOSW(PC,TC,W)

c     equation of state for computing mass inside chamber

      DOUBLE PRECISION PC,TC,W

#include "data.inc"
#include "constants.inc"

      W  = PC * Vc * MW / (PC * b + Ru * TC)

      END

      SUBROUTINE INTERP(T,X,Y,N,TINT,XINT,YINT)
c ---------------------------------------------------------------
c     Linear interpolation from data table.
c
c     Input:
c           T   = ordered array of length N representing the
```

```
c              data domain (must be either monotonically
c              increasing or descreasing).
c          X    = data array of length N.
c          Y    = data value of length N.
c          TINT = interpolation point.
c
c   Output:
c          XINT = interpolated X-value at point TINT
c          YINT = interpolated X-value at point TINT
c ---------------------------------------------------------------

      DOUBLE PRECISION T(*),X(*),Y(*),TINT,XINT,YINT
      DOUBLE PRECISION THETA
      SAVE JLO

      CALL HUNT(T,N,TINT,JLO)
      IF (JLO .LE. 0) THEN
        XINT = X(1)
        YINT = Y(1)
      ELSE IF (JLO .GE. N) THEN
        XINT = X(N)
        YINT = Y(N)
      ELSE
        THETA = (TINT - T(JLO))/(T(JLO+1)-T(JLO))
        XINT  = X(JLO) + THETA * (X(JLO+1) - X(JLO))
        YINT  = Y(JLO) + THETA * (Y(JLO+1) - Y(JLO))
      ENDIF

      END


      SUBROUTINE HUNT(XX,N,X,JLO)
c ---------------------------------------------------------------
c   Purpose: Search ordered list.
c
c   Source:  This subroutine was copied from the following book:
```

```
c
c          W.H. Press, B.P. Flannery, S.A. Teukolsky, W.T. Vetterling
c          Numerical Recipes
c          The Art of Scientific Computing
c          Cambridge University Press, New York, 1986.
c          Pages 91-92.
c
c   Input:
c        xx  = ordered array, must be either monotonically
c              increasing or descreasing
c        n   = length of array XX
c        x   = data value
c        jlo = initial guess for index search
c
c   Output:
c        jlo = index value for xx(jlo) <= x < xx(jlo+1),
c              jlo=0 or jlo=N indicates that x is out of
c              range.
c ---------------------------------------------------------------

      DOUBLE PRECISION XX(N),X
      LOGICAL ASCND
      ASCND = XX(N) .GT. XX(1)

      IF (JLO .LE. 0 .OR. JLO .GT. N) THEN
        JLO = 0
        JHI = N + 1
        GOTO 3
      ENDIF

      INC = 1
      IF (X .GE. XX(JLO) .EQV. ASCND) THEN
1       JHI = JLO + INC
        IF (JHI .GT. N) THEN
          JHI = N + 1
        ELSE IF (X .GE. XX(JHI) .EQV. ASCND) THEN
```

```
      JLO = JHI
      IN = INC + INC
      GOTO 1
    ENDIF
  ELSE
    JHI = JLO
2     JLO = JHI - INC
    IF (JLO .LT. 1) THEN
      JLO = 0
    ELSE IF (X .LT. XX(JLO) .EQV. ASCND) THEN
      JHI = JLO
      INC = INC + INC
      GOTO 2
    ENDIF
  ENDIF

3   CONTINUE

  IF (JHI - JLO .EQ. 1) RETURN

  JM = (JHI + JLO)/2
  IF (X .GT. XX(JM) .EQV. ASCND) THEN
    JLO = JM
  ELSE
    JHI = JM
  ENDIF

  GOTO 3
  END
```

==

Filename: data.inc

==

```
C-----------------------------------------------------------------
C Design Parameters:
C
```

```
C Vc    = volume of chamber [ft^3]
C A     = area of duct [ft^2]
C Cd    = discharge coefficient
C floss = fraction heat loss from tube
C
C TIMEX() = table from XKTC output of time values (ordered)
C PRESX() = table from XKTC output of gun pressure values (lb/ft^2)
C TEMPX() = table from XKTC output of gun temperature values (R)
C------------------------------------------------------------

      PARAMETER(NMAX  = 5000)
      DOUBLE PRECISION TIMEX(NMAX), PRESX(NMAX), TEMPX(NMAX)
      DOUBLE PRECISION FLOSS,A,Vc,Cd
      INTEGER NDATA

      COMMON /XKTC1/ TIMEX, PRESX, TEMPX
      COMMON /XKTC2/ NDATA
      COMMON /PARAM/ FLOSS,Vc,A,Cd

C------------------------------------------------------------
C Original problem:
C
C    floss = 0.85D0
C    Vc    = 0.005787D0
C    A     = 0.000608D0
C    Cd    = 0.62D0
C------------------------------------------------------------

============================================================
          Filename: constants.inc
============================================================
C------------------------------------------------------------
C Constants:
C
C R  = gas constant [ft-lb/(lb R)]
C MW = molecular weight [lb/lb-mole]
```

```
C  g  = gravitational acceleration [ft/sec^2]
C  Cv = constant volume heat capacity [ft-lb/(lb R)]
C  Cp = constant pressure heat capacity [ft-lb/(lb R)]
C  J  = convertion factor [ft-lb/Btu]
C  k  = ratio of Cp to Cv
C  Ru = universal gas constant  [ft-lb/(lb R mol)]
C  b  = specific covolume [ft^3/lb]
C-------------------------------------------------------------
      DOUBLE PRECISION R,MW,g,J,k,Cp,Cv,Ru,b

      PARAMETER(R  = 66.09D0)
      PARAMETER(MW = 23.36D0)
      PARAMETER(g  = 32.2D0)
      PARAMETER(J  = 778.0D0)
      PARAMETER(k  = 1.243D0)
      PARAMETER(Cp = 336.7D0)
      PARAMETER(Cv = 270.698D0)
      PARAMETER(Ru = 1544.0D0)
      PARAMETER(b  = 0.01649D0)

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